

LHC physics: the first one–two year(s)... *

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ABSTRACT: We discuss the strategy to commission the LHC experiments and understand standard physics at $\sqrt{s} = 14$ TeV before data taking starts and in the early phases of the LHC operation. In particular, we review the various steps needed to understand and calibrate the ATLAS and CMS detectors, from construction quality checks, to beam tests, to cosmics runs, to first collisions. We also review the preparation and tuning of Monte Carlo tools, and present a few examples of physics goals for integrated luminosities of up to a few fb^{-1} .

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1. Introduction

When the LHC will start providing data to the experiments, unprecedented opportunities to explore the frontier of high energy physics as we know it today will suddenly become available[1]. It will take some time before the accelerator ramps up in luminosity and the Collaborations debug and understand their detectors. Nevertheless it is crucial to realise that possible new exotic phenomena could have cross sections so large, and topologies so striking, that even a limited amount of collected data and a non-ultimate detector performance could lead to exciting results. Readiness to capture these opportunities is a must. Whether nature is kind to us and is preparing a sweet welcome to the TeV energy frontier, or whether we shall have to sweat through years of hard work before the total luminosity and the detector performance allow us to establish the existence of new phenomena, the preparation for the first phase of data taking, which includes both the definition of the strategies for the commissioning of the detectors and triggers and of the physics analyses, is therefore a task of great priority.

This presentation offers an elementary review of the physics landscape which ATLAS and CMS could be exposed to in the early days of running, and discusses the efforts which are taking place to ensure a prompt exploitation of the new data.

2. Physics opportunities at the beginning

In the Fall of 1982 the first extended physics run of UA1 and UA2 took place at the CERN $S\bar{p}pS$ collider, at $\sqrt{S} = 546$ GeV. The maximum luminosity was a mere $\mathcal{L} = 5 \times 10^{28} \text{cm}^{-2}\text{s}^{-1}$ ($\sim 1\%$ of the asymptotic one), with a total sample of $\sim 20\text{nb}^{-1}$ integrated over 30 days. The outcome of this run was nevertheless a big hit: the discovery of W and Z bosons, established after only few months of hard work[2]. However tough the new experimental environment, however weak the understanding of physics at those unprecedented energies (jets had only been first observed few months earlier, after a yet shorter pilot run in 1981 [3]), the rate and features of the signal were such that it could not be missed. This was not a surprise: a key role was played by the energy, which being almost a factor of 10 larger than the previous frontier, the ISR, opened up the required phase space.

Few years later, in the Summer of 1987, the first physics run for CDF at the Fermilab Tevatron collider ($\sqrt{S} = 1.8$ TeV) took place, again at $\mathcal{L} = 5 \times 10^{28} \text{cm}^{-2}\text{s}^{-1}$ ($\sim 1\%$ of the design value), with a total of $\sim 20\text{nb}^{-1}$. Nothing new emerged from this run, and it did take some time after that before CDF could start exploring truly new territory. The reason is that the jump in energy by a factor of 3 was not large enough to compensate for the integrated luminosity already accumulated by UA1 and UA2. Over 100nb^{-1} would have been necessary to improve on, say, the top quark search, as the production cross section at the Tevatron was “only” a factor of 10-20 larger than at CERN, in the relevant range of masses.

When the LHC will start, the situation will be much more like that at the time of the $S\bar{p}pS$ turn on. In spite of the multi-fb $^{-1}$ luminosity which we expect CDF and D0 to collect by that time, rates for new particles (heavy quarks, gluinos, new gauge bosons, etc.) with mass beyond the discovery reach of the Tevatron will allow their abundant production already with typical start-up luminosities of 1% of the design, namely $\mathcal{L} \sim 10^{31-32} \text{cm}^{-2}\text{s}^{-1}$. This is clearly shown in fig. 1, which plots the production rate for pairs of new heavy quarks (already at the rather low mass of the top quark the rate at the LHC is over 100 times larger than at the Tevatron!). Knowing that cross sections for gluinos are typically one order of magnitude larger than for quarks of equal mass, this figure gives also a clear picture of the immense Supersymmetry (SUSY) discovery potential of early LHC data!

So, we have phase-space, we have large rates for new physics. But should we seriously expect something to show up at the LHC energy scale and at luminosities reachable early on? The Tevatron and LEP’s heritage is a strong confirmation of the Standard Model (SM), and at the same time an apparent paradox[4], illustrated in the following paragraphs. Electroweak (EW) precision tests and the value of the top mass are consistent with, and require, a rather light Higgs mass: $m_H = 117_{-68}^{+45}$ GeV; EW radiative corrections in the SM, integrated up to a scale Λ , shift the bare value of m_H by:

$$\delta m_H^2 = \frac{6G_F\Lambda^2}{\sqrt{2}\pi^2} (m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_H^2) \sim (115 \text{ GeV})^2 \left(\frac{\Lambda}{400 \text{ GeV}} \right)^2. \quad (2.1)$$

The integration in principle can extend up to very large values of Λ , where new particles may appear, changing eq. (2.1). As Λ gets significantly larger than 400 GeV, however, the

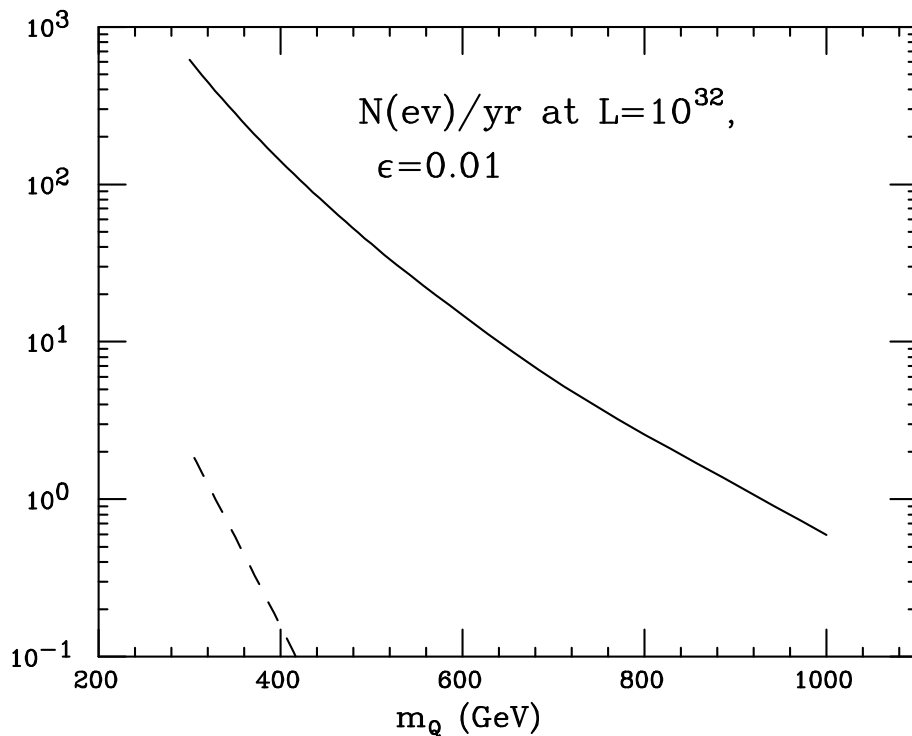


Figure 1: Production rates for heavy quark pairs, as a function of the quark mass, at the Tevatron (dashed) and at the LHC (solid), during one year of data taking at $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, and assuming a detection efficiency of 1%.

presence of a counterterm (CT) should be assumed, to ensure that the overall value of m_H is consistent with its bounds. This CT can be interpreted as a low-energy manifestation of the physical mechanisms which, at some scale $\bar{\Lambda}$, modify eq. (2.1). Ensuring that the residual of the cancellation between eq. (2.1) and the CT is in the 100 GeV range, however, forces a fine tuning which becomes more and more unbelievable as $\bar{\Lambda}$ grows. Assuming that no new physics appears before the GUT scale of 10^{16} GeV would lead to a level of fine tuning of 10^{-28} ! By and large theorists believe that this is unlikely enough to call for the existence of new physics at scales in the range of 1–few TeV, so as to maintain the fine tuning level to within $\mathcal{O}(10^{-3})$. This belief however clashes (and this is where the paradox arises) with the staggering agreement between EW data and the SM. The inclusion of generic new physics, parameterized in terms of low-energy effective couplings between the SM particles, and the analysis of the effects induced on EW observables, set lower limits to the scale $\bar{\Lambda}$ in the range of 5–10 TeV[5], at the extreme limit of the fine-tuning window. The solution to the paradox could only be obtained with new physics which cancels the large radiative contributions to m_H and, at the same time, manages to leave all other EW parameters and observables unaffected. SUSY provides one such example! The cancellation of large loop effects between SM particles and their SUSY partners modifies eq. (2.1) and

leads to an upper limit on m_H , given in a simplified approximation here:

$$m_H^2 \lesssim m_Z^2 + \frac{3G_F m_t^4}{\sqrt{2}\pi^2} \log \left(\frac{m_t^2}{m_t^2} \right) \quad (2.2)$$

where m_t^2 is the average squared mass of the two stop states. At the same time, the structure of the theory is such that indeed generic choices of the SUSY parameters, consistent with current experimental limits on new particles, lead to negligible effects in the EW observables. In the minimal realization of SUSY (MSSM), when eq. (2.2) is improved with 2-loop and non-logarithmic corrections, the experimental limit on m_H pushes however the scale of SUSY in the multi-TeV domain. Once again this is at the edge of being acceptable as a “natural” solution to the fine-tuning problem, and for many theorists the room left for SUSY is becoming too tight. As a result, new scenarios for EW symmetry breaking, particularly some where the upper limits on the Higgs mass are looser compared to the MSSM, have been proposed (as reviewed in[4]).

While these alternative scenarios could take much longer to be identified experimentally, the SUSY framework provides a strong and appealing physics case for possible early discovery, and therefore should be given maximum priority in the planning for the first data analyses. SUSY is in fact expected to manifest itself with abundant and striking signals, such as the production of multijets with large missing transverse energy (\cancel{E}_T), multileptons (possibly same-charge), or prompt photons with large \cancel{E}_T . Because of rates, background levels, and nature of the observables, searches for SUSY are expected to be less demanding from the experimental point of view than the quest for the Higgs in the $m_H < 140$ GeV range. In addition, SUSY provides a natural candidate for dark matter, namely the lightest neutralino χ_1^0 , the neutral SUSY partner of the photon and Z . Proving the direct link between dark matter and SUSY would be, perhaps even more than the Higgs discovery, the flagship achievement of the LHC! Last but not least, an early detection of SUSY could immediately provide clear directions to the field of experimental high-energy physics, and allow a robust planning for future facilities.

3. Machine start-up scenario

According to the present LHC schedule (see[6] for more details), the machine will be cooled down in Spring 2007, and will then be commissioned for a few months starting with single beams. A first run with colliding beams is expected in the second half of 2007, and will likely be followed by a shut-down of a few months, and then by a seven-month physics run in 2008 at instantaneous luminosities of up to $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

There are several uncertainties on this plan (in particular because of the recent problems with the production of the cryogenic line) and on how the machine commissioning and performance will actually evolve. Therefore we assume here that the integrated luminosity collected by the end of 2008 will range between a very modest 100 pb^{-1} per experiment and a very ambitious 10 fb^{-1} per experiment, and we discuss the LHC physics potential for this range.

Table 1: *Examples of expected detector performance for ATLAS and CMS at the time of the LHC start-up, and of physics samples which will be used to improve this performance.*

	expected performance on “day 1”	data samples (examples) to improve the performance
ECAL uniformity	$\sim 1\%$ ($\sim 4\%$) in ATLAS (CMS)	minimum-bias, $Z \rightarrow ee$
electron energy scale	1-2%	$Z \rightarrow ee$
HCAL uniformity	2-3%	single pions, QCD jets
jet energy scale	$\leq 10\%$	$Z(\rightarrow \ell\ell)+\text{jet}$, $W \rightarrow jj$ in $t\bar{t}$ events
tracker alignment	20-200 μm in $R\phi$	generic tracks, isolated μ , $Z \rightarrow \mu\mu$

4. Initial detectors and initial performance

The first question to address is which detectors will be available at the beginning. Indeed, because of missing resources, and in some cases of construction delays, several components of ATLAS and CMS will not be complete at the beginning of data taking. ATLAS will start with two pixel layers (instead of three) and without Transition Radiation Tracker in the region $2 < |\eta| < 2.4$. CMS will start without muon trigger chambers (RPC) in the region $1.6 < |\eta| < 2.1$ and without the fourth layer of the end-cap muon chambers. Furthermore, the CMS end-cap electromagnetic calorimeter and pixel detector will be installed during the shut-down period after the 2007 run. In addition, in both experiments part of the high-level trigger and data acquisition processors will be deferred, with the consequence that the output rate of the level-1 trigger will be limited to 50 kHz (instead of 100 kHz) in CMS and to 35 kHz (instead of 75 kHz) in ATLAS.

The impact of this staging on physics will be significant but not dramatic. The main loss is a descoped B -physics programme because, due to the reduced level-1 bandwidth, the thresholds of the single-muon triggers will have to be raised from a few GeV (as originally chosen to address B -physics studies) to $p_T=14\text{--}20$ GeV.

The second question concerns the detector performance to be expected on “day 1”, i.e. at the moment when data taking starts. Some predictions, based on construction quality checks, on the known precision of the hardware calibration and alignment systems, on test-beam measurements and on simulation studies, are given in tab. 1 for illustration. The initial uniformity of the electromagnetic calorimeters (ECAL) should be at the level of 1% for the ATLAS liquid-argon calorimeter and 4% for the CMS crystals, where the difference comes from the different techniques and from the limited time available for test-beam measurements in CMS. Prior to data taking, the jet energy scale may be established to about 10% from a combination of test-beam measurements and simulation studies. The tracker alignment in the transverse plane is expected to be known at the level of 20 μm in the best case from surveys, from the hardware alignment systems, and possibly from some studies with cosmic muons and beam halo events.

This performance should be significantly improved as soon as the first data will be available (see last column in tab. 1) and, thanks to the huge event rates expected at the LHC, the ultimate statistical precision should be achieved after a few days/weeks of

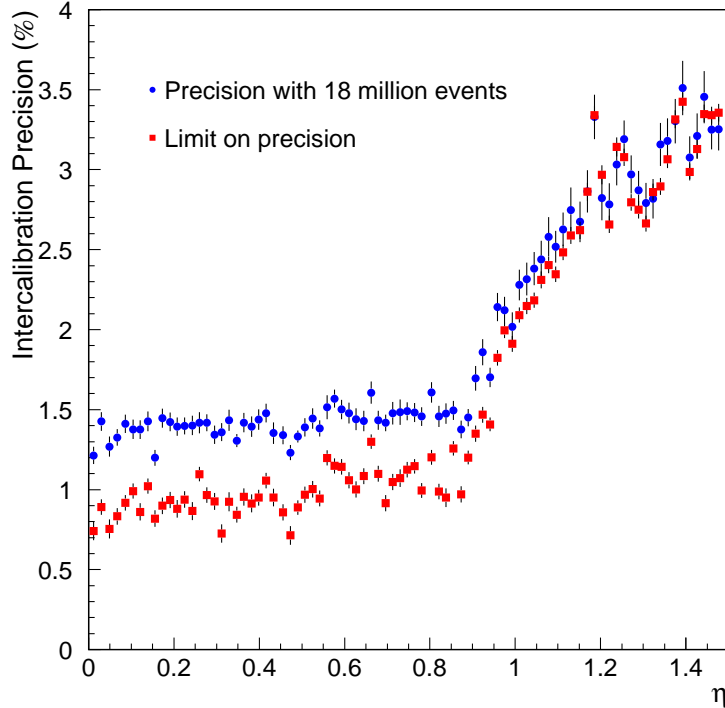


Figure 2: *Inter-calibration precision of the CMS electromagnetic calorimeter achievable with 18 million minimum-bias events[7], as a function of rapidity (dots). The squares show the limit coming from the non-uniformity of the upstream material.*

data taking. Then the painful battle with the systematic uncertainties will start. This is illustrated in fig. 2 which shows that, by measuring the energy flow in about 18 million minimum-bias events (which can be collected in principle in a few hours of data taking), the non-uniformity of the CMS ECAL should be reduced from the initial 4% to about 1.5% in the barrel region. Therefore the systematic limit coming from the non-uniformity of the upstream tracker material will be hit very quickly.

5. Strategy to achieve the goal detector performance

Are the performance expectations presented in the previous section realistic? This is discussed below with the help of a concrete example.

The ATLAS and CMS detectors have been subject to stringent requirements and detailed quality controls at the various steps of the construction phase. Extensive test-beam measurements have been performed with prototype and final detector modules, which have also allowed the validation of the simulation packages (e.g. GEANT4) used for instance to extrapolate the detector response from the test-beam to the collider environment. Such detailed checks and tests represent an unprecedented culture in our field. In addition, *in situ*

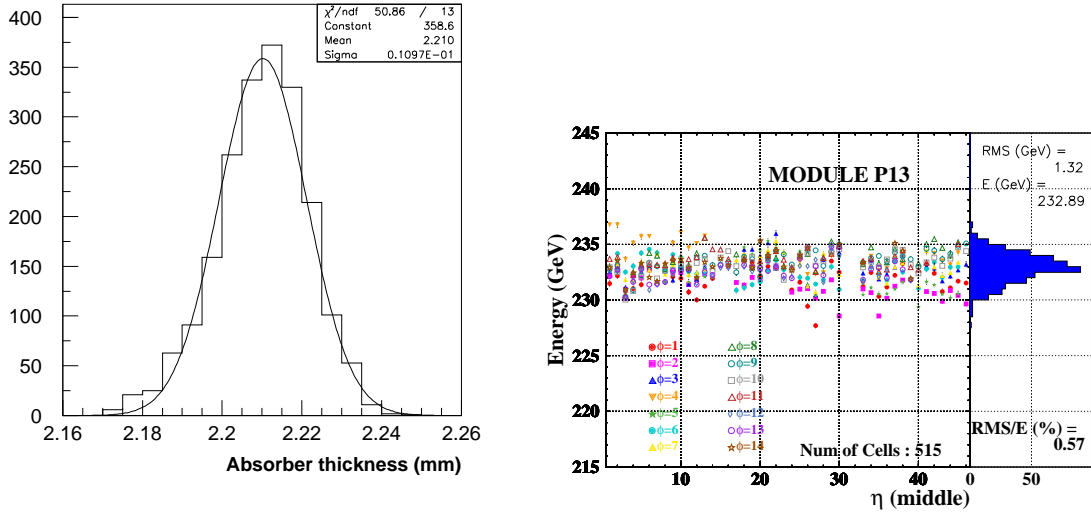


Figure 3: Left: Distribution of the thickness of the 2048 absorber plates (3 m long and 0.5 m wide) of the ATLAS barrel ECAL, as obtained from ultrasound measurements. The mean value of the distribution is 2.2 mm and the r.m.s. is 11 μm . Right: Energy response of one module (of size $\Delta\eta \times \Delta\phi = 1.4 \times 0.4$) of the ATLAS barrel ECAL, as a function of rapidity, as measured from a scan with test-beam electrons. The various symbols indicate different ϕ rows.

commissioning and calibrations after installation in the pits will be needed to understand the experiments as a whole, to account for the presence of e.g. upstream material and magnetic field, to cure long-range effects, etc. These calibrations will be based on cosmic muons, beam-halo muons and beam-gas events during the pre-collision phase (i.e. in the first half of 2007, during the machine cool-down and single-beam commissioning). Then, as soon as first collisions will be available, well-known physics samples (e.g. $Z \rightarrow \ell\ell$ events, see tab. 1) will be used.

As an example of the above procedure, the case of the ATLAS lead-liquid argon electromagnetic calorimeter[8], for which the construction phase is completed, is discussed below.

One crucial performance issue for the LHC electromagnetic calorimeters is to provide a mass resolution of about 1% in the hundred GeV range, needed to observe a possible $H \rightarrow \gamma\gamma$ signal as a narrow peak on top of the huge $\gamma\gamma$ irreducible background. This requires a response uniformity, that is a total constant term of the energy resolution, of $\leq 0.7\%$ over the full calorimeter coverage ($|\eta| < 2.5$). Achieving this goal is challenging, especially at the beginning, but is necessary for a fast discovery, and can hopefully be accomplished in four steps:

- Construction quality. Test-beam measurements performed with prototypes of the ATLAS ECAL in the early '90s showed that a 1% excess in the thickness of the lead plates produces a drop of the calorimeter response by 0.7%. Therefore, in order to keep the maximum response non-uniformity coming from the detector mechanics

alone below 0.3%, the thickness of the lead plates must be uniform to about 0.5%, i.e. $\sim 10 \mu\text{m}$. This goal has been achieved, as shown in the left panel of fig. 3.

- Test-beam measurements. About 15% of the final calorimeter modules have been exposed to electron beams, in order to verify the construction uniformity and to prepare correction factors to the detector response. The right panel in fig. 3 shows the results of a position scan of one module performed with high-energy test-beam electrons. For all tested modules, the response non-uniformity was found to be about 1.5% before correction, i.e. at the exit of the construction chain, and better than 0.7% after calibration with test-beam data.
- Pre-collision phase. Before data taking starts, the calorimeter calibration can be checked *in situ* with physics-like signals by using cosmic muons. Table 2 shows the expected rates of cosmics in ATLAS[9] as obtained from a full simulation of the detector inside the underground cavern (including the overburden, the access shafts and the surface buildings). These results have also been validated by direct measurements of the cosmics flux in the pit made with a scintillator telescope. It can be seen that rates between 0.5 Hz and 30 Hz are expected, depending on the requirements on the muon trajectory. Therefore, in about three months of cosmics runs in 2007 during the machine cool-down and commissioning, a few million events should be collected, a data sample large enough to catalog and fix several problems, gain operational experience, check the relative timing and position of the various sub-detectors, etc., hopefully in a more relaxed environment than during the collision phase.

In particular, for what concerns the electromagnetic calorimeter, the signal-to-noise ratio for muons is large enough ($S/N \sim 7$ from test-beam measurements) that cosmic muons can be used to check the calibration uniformity of the barrel calorimeter as a function of rapidity. The calorimeter is equipped with an electronics calibration system delivering pulses uniform to 0.25%. However, the calibration signals and the physics signals do not have exactly the same shape, and the difference depends on the rapidity of a given calorimeter cell. This induces a non-uniformity of the ECAL response to incident particles as a function of η . Test-beam studies show that the expected sample of cosmic muons is large enough to allow measurements of these effects down to the 0.5% level.

- First collisions. As soon as first collider data will be available, $Z \rightarrow ee$ events, which are produced at the rate of $\sim 1 \text{ Hz}$ at a luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, will be used to correct long-range response non-uniformities from module to module, possible temperature effects, the impact of the upstream material, etc. Full simulation studies indicate that, since the calorimeter is already quite uniform on “day 1” by construction and thanks to the previous steps, about $10^5 Z \rightarrow ee$ events should be sufficient to achieve the goal overall constant term of 0.7%. In addition, this $Z \rightarrow ee$ sample should fix the absolute energy scale to about 0.5%. Therefore, after a few weeks of data taking the ATLAS ECAL should in principle be fairly well calibrated.

Table 2: *Expected rates of cosmic muons in ATLAS for various requirements on the muon trajectory, as obtained from a full simulation of the detector inside the pit.*

topology	rate (Hz)	comments
through-going muons	~ 25	muons giving hits on top and bottom RPC's and in inner detector
close to interaction vertex	~ 0.5	muons passing within $ z < 60$ cm and $R < 20$ cm from the interaction centre
useful for ECAL calibration	~ 0.5	muons with $ z < 20$ cm, $E_{\text{cell}} > 100$ MeV

As an academic exercise, one could consider a very pessimistic (actually unrealistic...) scenario. That is, ignoring the results and expectations discussed above, one could assume that no corrections (neither based on test-beam data, nor using $Z \rightarrow ee$ events) will be applied. In this case, the intrinsic calorimeter constant term would be given by the uncorrected non-uniformity from detector construction (measured to be $\sim 1.5\%$, as mentioned above), to which another $\sim 1.5\%$ from uncorrected material effects has to be added. This would give a total constant term of the energy resolution of about 2% instead of 0.7%. As a consequence, the significance of a $H \rightarrow \gamma\gamma$ signal would be reduced by about 30%, and a factor 1.7 more integrated luminosity would be needed to achieve the same sensitivity.

6. How well will LHC physics and Monte Carlos be known before data taking starts?

While we cannot anticipate which new physics is waiting for us at the LHC, we do know that there is plenty of SM processes to be observed. In many cases, these processes offer themselves the potential for important measurements (e.g. improved determinations of the W and top-quark masses, parton densities). More in general, they will provide dangerous backgrounds to most signals of new physics. A solid physics programme at the LHC will therefore require a robust understanding of SM processes, and of QCD in particular. Significant improvements have taken place in the past few years, as reviewed in[10] and shortly summarized here.

By far the cleanest process in pp collisions, theoretically as well as experimentally, is the production of W and Z bosons. In addition to the full NNLO predictions for the total cross sections, achieved long ago[11], NNLO calculations for the experimentally more interesting rapidity distributions have recently been obtained[12], reducing the intrinsic theoretical uncertainty for Drell-Yan cross sections to the level of 1-2%. At this level of accuracy, EW effects start playing a role, as recently evaluated in[13], and a precise knowledge of the parton densities (PDF) becomes essential. Progress in this field, in addition to the availability of much more accurate data from HERA[14], has been driven by the development of formalisms which allow a proper account of systematic uncertainties[15].

The production of $t\bar{t}$ pairs, which at the Tevatron represents a rather exotic signature, will become at the LHC a dangerous background, with an inclusive rate of the order of 1 Hz. The cross section is known from theory with an accuracy of about 5%[16], enough to allow

an indirect estimate of the top mass with an accuracy of ± 2 GeV (excluding experimental uncertainties). The ability to precisely model the structure of the final states has improved recently with the development of the MC@NLO code, where the complete NLO parton-level matrix elements are consistently incorporated in a full shower Monte Carlo (MC)[17]. Also the description of bottom quark production appears now to be under better theoretical control, after improvements in the inputs of the calculations (fragmentation functions and resummation of large logarithms) have led to excellent agreement[18] with the most recent results from CDF[19].

Complex multijet topologies can be described today more reliably, thanks to recent advances in the calculation of multiparton final states[20], their inclusion in parton level codes[21, 22], and the development of techniques to deal with the problem of properly merging with shower MCs[23]. In addition, the well known and tested shower MC codes which dominated the LEP and Tevatron era are being updated, with inclusion of better algorithms for the development of the shower or for the description of the underlying event[24].

Validation of these new tools using Tevatron data will be possible before the LHC starts, but only the very large statistics and the huge dynamic range of the LHC will allow complete studies and proper tunings.

7. Early physics goals and measurements

Table 3 shows the data samples expected to be recorded by ATLAS and CMS for some example physics processes and for an integrated luminosity of 10 fb^{-1} . The trigger selection efficiency has been included. Already over the first year (even days in some cases) of operation, huge event samples should be available from known SM processes, which will allow ATLAS and CMS to commission the detectors, the software and the physics itself, and also from several new physics scenarios. We stress that this will be the case even if the integrated luminosity collected during the first year were to be a factor of hundred smaller, i.e. $\sim 100 \text{ pb}^{-1}$.

In more detail, the following goals can be addressed with such data samples¹:

- Commission and calibrate the detectors *in situ*, as already mentioned. Understanding the trigger performance in as an unbiased way as possible, with a combination of minimum-bias events, QCD jets collected with various thresholds, single and dilepton samples, is going to be one of the most challenging and crucial steps at the beginning. $Z \rightarrow \ell\ell$ is a gold-plated process for a large number of studies, e.g. to set the absolute electron and muon scales in the ECAL and tracking detectors respectively, whereas $t\bar{t}$ events can be used for instance to establish the absolute jet scale and to understand the b -tagging performance.

¹It should be noted that the total amount of data recorded by each experiment in one year of operation corresponds to about 1 Petabyte, which represents an unprecedented challenge also for the LHC computing and offline software.

Table 3: For some physics processes, the numbers of events expected to be recorded by ATLAS and CMS for an integrated luminosity of 10 fb^{-1} per experiment.

channel	recorded events per experiment for 10 fb^{-1}
$W \rightarrow \mu\nu$	7×10^7
$Z \rightarrow \mu\mu$	1.1×10^7
$t\bar{t} \rightarrow \mu + X$	0.08×10^7
QCD jets $p_T > 150 \text{ GeV}$	$\sim 10^7$ (assuming 10% of trigger bandwidth)
minimum bias	$\sim 10^7$ (assuming 10% of trigger bandwidth)
$\tilde{g}\tilde{g}$, $m(\tilde{g}) \sim 1 \text{ TeV}$	$10^3 - 10^4$

- Perform extensive measurements of the main SM physics processes, e.g. cross sections and event features for minimum-bias, QCD dijet, $W, Z, t\bar{t}$ production, etc. These measurements will be compared to the predictions of the MC simulations, which will already be quite constrained from theory and from studies at the Tevatron and HERA energies. Typical initial precisions may be 10-20% for cross section measurements, and 5-7 GeV on the top-quark mass, and will likely be limited by systematic uncertainties after just a few weeks of data taking.
- Prepare the road to discoveries by measuring the backgrounds to possible new physics channels. Processes like W/Z +jets, QCD multijet production and $t\bar{t}$ are omnipresent backgrounds for a large number of searches and need to be understood in all details. In addition, dedicated control samples can be used to measure specific backgrounds. For instance, $t\bar{t}jj$ production, where the jets j are tagged as light-quark jets, can be used to gauge the irreducible $t\bar{t}b\bar{b}$ background to the $t\bar{t}H \rightarrow t\bar{t}b\bar{b}$ channel.

As an example of initial measurement with limited detector performance, fig. 4 shows the reconstructed top-quark signal in the gold-plated $t\bar{t} \rightarrow bj\bar{j} b\ell\nu$ semileptonic channel, as obtained from a simulation of the ATLAS detector. The event sample corresponds to an integrated luminosity of 150 pb^{-1} , which can be collected in less than one week of data taking at $L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. A very simple analysis was used to select these events, requiring an isolated electron or muon with $p_T > 20 \text{ GeV}$ and four and only four jets with $p_T > 40 \text{ GeV}$. The invariant mass of the three jets with the highest p_T was then plotted. No kinematic fit was made, and no b -tagging of some of the jets was required, assuming conservatively that the b -tagging performance would not have been well understood yet. Figure 4 shows that, even under these over-pessimistic conditions, a clear top signal should be observed above the background after a few weeks of data taking (30 pb^{-1} would be sufficient). In turn, this signal can be used for an early validation of the detector performance. For instance, if the top mass is wrong by several GeV, this would indicate a problem with the jet energy scale. Furthermore, top events are an excellent sample to understand the b -tagging performance of ATLAS and CMS. It should be noted that, unlike at the LHC, at the Tevatron today the statistics of $t\bar{t}$ events is not sufficient to use these samples for detector calibration purposes.

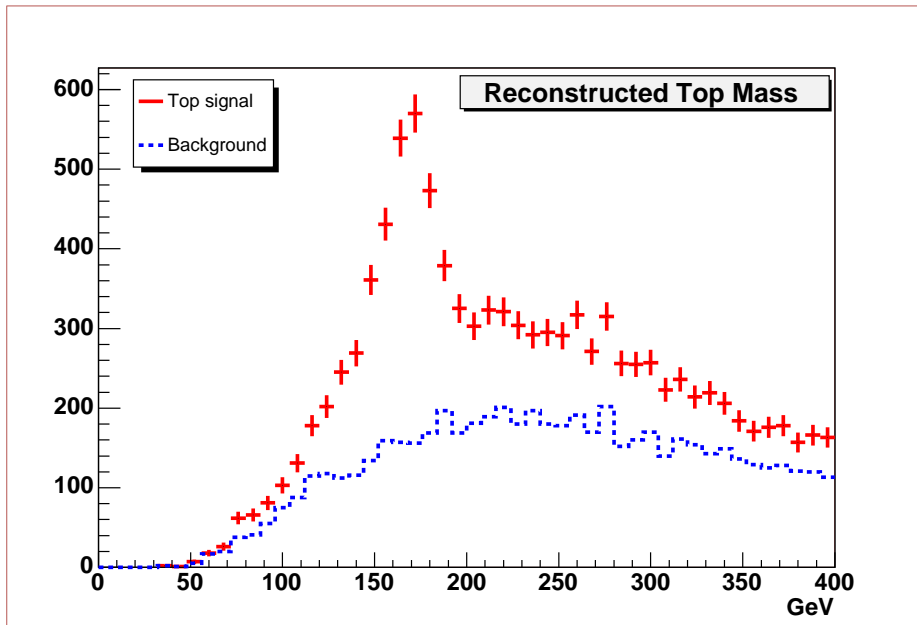


Figure 4: Three-jet invariant mass distribution for events selected as described in the text, as obtained from a simulation of the ATLAS detector. The dots with error bars show the expected signal from $t\bar{t}$ events plus the background, the dashed line shows the $W+4$ -jet background alone (ALPGEN Monte Carlo[22]). The number of events corresponds to an integrated luminosity of 150 pb^{-1} .

8. Early discoveries

Only after the three steps outlined in section 7 will have been fully addressed can the LHC experiments hope to extract a convincing discovery signal from their data. Three examples of new physics are discussed briefly below, ranked by increasing difficulty for discovery in the first year(s) of operation: an easy case, namely a possible $Z' \rightarrow e^+e^-$ signal, an intermediate case, SUSY, and a difficult case, a light Standard Model Higgs boson.

8.1 $Z' \rightarrow e^+e^-$

A particle of mass 1-2 TeV decaying into e^+e^- pairs, such as a possible new gauge boson Z' , is probably the easiest object to discover at the LHC, for three main reasons. First, if the branching ratio into leptons is at least at the percent level as for the Z boson, the expected number of events after all experimental cuts is relatively large, e.g. about ten for an integrated luminosity as low as 300 pb^{-1} and a particle mass of 1.5 TeV. Second, the dominant background, dilepton Drell-Yan production, is small in the TeV region, and even if it were to be a factor of two-three larger than expected today (which is unlikely for such a theoretically well-known process), it would still be negligible compared to the signal. Finally, the signal will be indisputable, since it will appear as a resonant peak on top of a smooth background, and not just as an overall excess in the total number of events. These

expectations are not based on ultimate detector performance, since they hold also if the calorimeter response is understood to a conservative level of a few percent.

8.2 Supersymmetry

Extracting a convincing signal of SUSY in the early phases of the LHC operation is not as straightforward as for the previous case, since good calibration of the detectors and detailed understanding of the numerous backgrounds are required. As soon as these two pre-requisites are satisfied, observation of a SUSY signal should be relatively easy and fast. This is because of the huge production cross sections, and hence event rates, even for squark and gluino masses as large as ~ 1 TeV (see tab. 3), and the clear signature of such events in most scenarios. Therefore, by looking for final states containing several high- p_T jets and large \cancel{E}_T , which is the most powerful and model-independent signature if R-parity is conserved, the LHC experiments should be able to discover squarks and gluinos up to masses of ~ 1.5 TeV in only one month of data taking at $L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, as shown in the left panel of fig. 5.

Although detailed measurements of the SUSY particle masses will likely take several years, it should nevertheless be possible to obtain a first determination of the SUSY mass scale quickly after discovery. This is illustrated in the right panel of fig. 5, which shows the striking SUSY signal on top of the SM background, expected at a point in the minimal SUGRA parameter space where squark and gluino masses are about 700 GeV. The plotted variable, called “effective mass” (M_{eff}), is defined as the scalar sum of the event \cancel{E}_T and of the transverse energies of the four highest p_T jets, and thus reflects the “heaviness” of the particles produced in the final state. More precisely, the position of the peak of the M_{eff} signal distribution (see fig. 5) moves to larger/smaller values with increasing/decreasing squark and gluino masses. Therefore a measurement of the signal peak position should provide a first fast determination of the mass scale of SUSY. The expected precision is about 20% for an integrated luminosity of 10 fb^{-1} , at least in minimal models like mSUGRA.

A crucial detector performance issue for an early SUSY discovery is a reliable reconstruction of the event \cancel{E}_T , which is *a priori* prone to contamination from several instrumental effects (calorimeter non-linearities, cracks in the detector, etc.). Final states with non-genuine \cancel{E}_T can be rejected by requiring the event primary vertex to be located close to the interaction centre (which also helps to suppress the background from cosmic and beam-halo muons), no jets pointing to detector cracks, and that the missing p_T vector is not aligned with any jet. The calorimeter response linearity can be understood to a large extent by using “calibration” samples like $Z(\rightarrow \ell\ell)+\text{jet}$ events (with $\ell = e, \mu$), where the lepton pair and the jet are back-to-back in the transverse plane, so that the well-measured p_T of the lepton pair can be used to calibrate the jet p_T scale over a large dynamic range.

Concerning the physics backgrounds (e.g. $Z \rightarrow \nu\bar{\nu}+\text{jets}$, $t\bar{t}$ production, QCD multijet events), most of them can be measured by using control samples. For instance, $Z \rightarrow \ell\ell+\text{jet}$ production provides a normalization of the $Z \rightarrow \nu\bar{\nu}+\text{jets}$ background. More difficult to handle is the residual background from QCD multijet events with fake \cancel{E}_T produced by the above-mentioned instrumental effects. The technique used at the Tevatron consists of normalizing the Monte Carlo simulation to the data in the (signal-free) region at low \cancel{E}_T ,

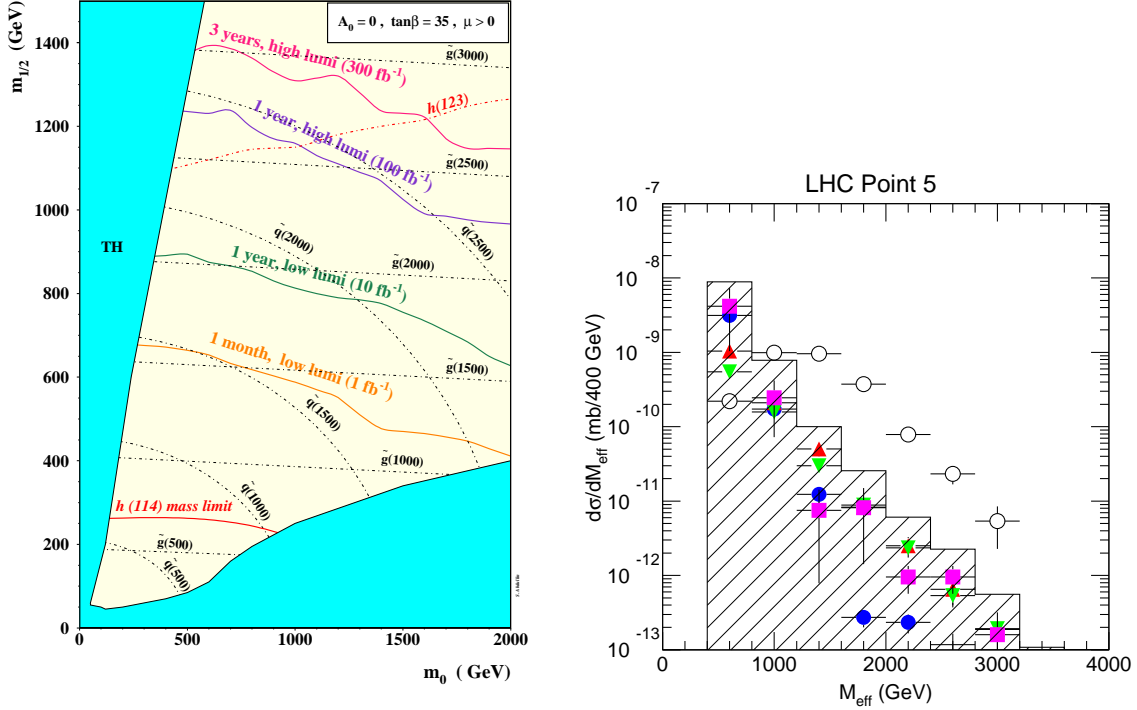


Figure 5: *Left: The CMS discovery potential[25] for squarks and gluinos in mSUGRA models, parametrized in terms of the universal scalar mass m_0 and universal gaugino mass $m_{1/2}$, as a function of integrated luminosity. Squark and gluino mass isolines are shown as dot-dashed lines (masses are given in GeV). Right: The expected distribution of the effective mass (see text) for the SUSY signal at “Point 5”[26] of the mSUGRA parameter space (open circles), as obtained from a simulation of the ATLAS detector. The histogram shows the total SM background, which includes $t\bar{t}$ (solid circles), W +jets (triangles), Z +jets (downward triangles), and QCD jets (squares).*

and then use the Monte Carlo to predict the background in the (potentially signal-rich) region at large \cancel{E}_T .

A crucial element in the ability to calibrate these backgrounds using the theoretical MC predictions to extrapolate from the signal-free to the signal-rich regions is the reliability of the MC themselves. As mentioned earlier, their level of accuracy and their capability to describe complex final states, such as the multijet topology typical of new phenomena like SUSY, have improved significantly over the past few years[10]. In some cases, the predictions obtained with the new tools are very different from those derived in the past. In particular, the description of multijet final states, which until the recent past could only be achieved in a rather approximate way with shower MCs, is now performed starting from exact matrix-element calculations of the multiparton emission amplitudes. This typically results in higher production rates, increasing therefore the difficulty of extracting in a robust way the signals of new physics from the QCD backgrounds. An example of this is shown in fig. 6: the diamond plot represents the matrix-element prediction[22] of the

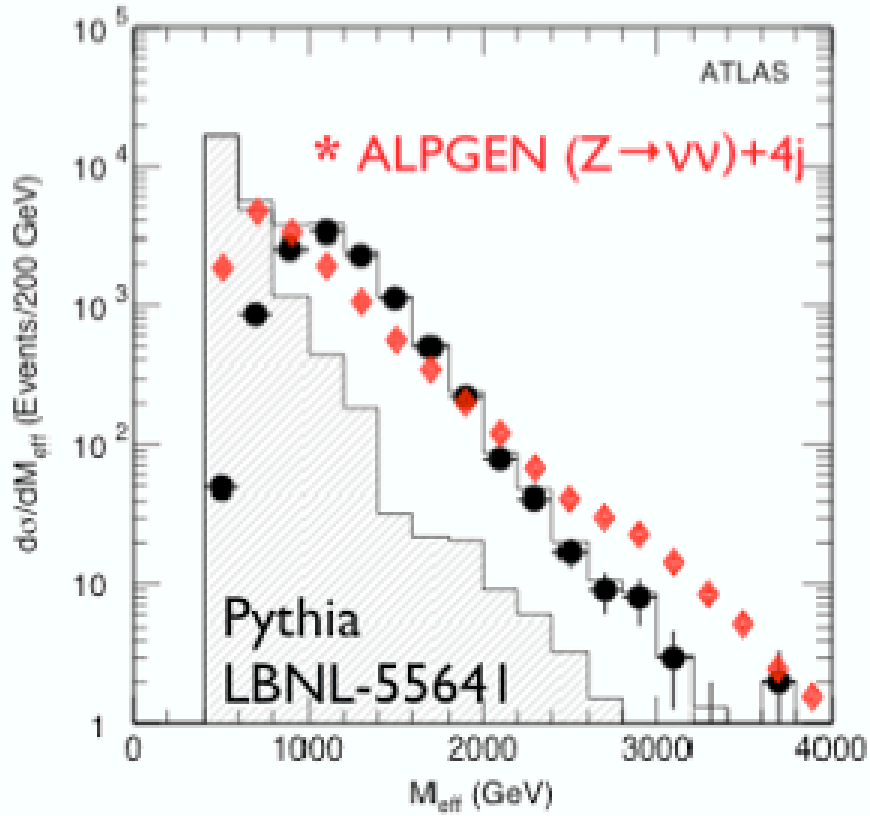


Figure 6: M_{eff} distributions for a potential SUSY signal (histogram), separated into signal (dark points) and the background prediction from shower MC (shaded histogram), compared to the $Z(\rightarrow \nu\bar{\nu})+4\text{jet}$ background evaluated with exact matrix elements (grey diamonds).

$Z(\rightarrow \nu\bar{\nu})+4\text{jet}$ background to a possible multijet+ \cancel{E}_T SUSY signal, compared to estimates (the grey histogram, which also includes the contribution of \cancel{E}_T -mismeasurement in pure multijet events) obtained in the past with standard shower MC simulations. Not only is the rate larger than previously expected, but the shape of the distribution is different, and much closer to that of the signal itself. A calibration of the absolute rate using $(Z \rightarrow \ell^+ \ell^-)+4\text{jet}$ data is still possible where the statistics allow (up to $M_{\text{eff}} \sim 1-2$ TeV), but a validation of the MCs is clearly required to ensure a robust extrapolation to the highest values of M_{eff} .

8.3 Standard Model Higgs boson

The possibility of discovering a SM Higgs boson at the LHC during the first year(s) of operation depends very much on the Higgs mass, as shown in fig. 7. If the Higgs mass is larger than 180 GeV, discovery may be relatively easy thanks to the gold-plated $H \rightarrow 4\ell$ channel, which is essentially background-free. The main requirement in this case is an integrated luminosity of at least $5-10 \text{ fb}^{-1}$, since the signal has a cross section of only a few fb.

The low-mass region close to the LEP limit is much more difficult. The expected

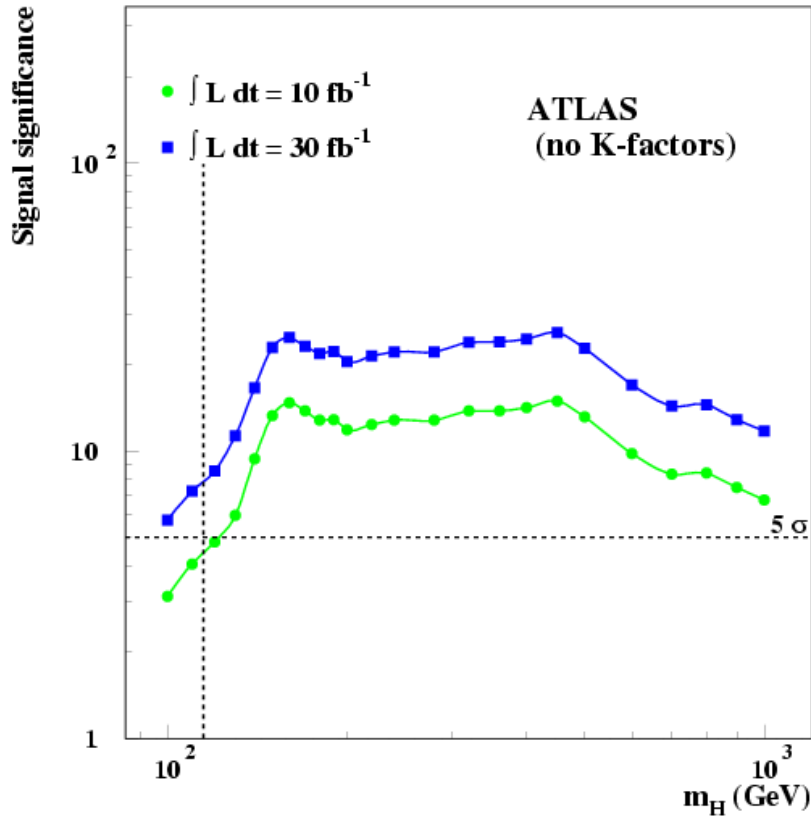


Figure 7: The expected signal significance for a SM Higgs boson in ATLAS as a function of mass, for integrated luminosities of 10 fb^{-1} (dots) and 30 fb^{-1} (squares). The vertical line shows the lower limit from searches at LEP. The horizontal line indicates the minimum significance (5σ) needed for discovery.

sensitivity for a Higgs mass of 115 GeV and for the first good (i.e. collected with well-calibrated detectors) 10 fb^{-1} is summarized in tab. 4. The total significance of about 4σ per experiment ($4^{+2.2}_{-1.3} \sigma$ including the expected systematic uncertainties) is more or less equally shared among three channels: $H \rightarrow \gamma\gamma$, $t\bar{t}H$ production with $H \rightarrow b\bar{b}$, and Higgs production in vector-boson fusion followed by $H \rightarrow \tau\tau$. A conservative approach has been adopted in deriving these results. For instance, very simple cut-based analyses have been used, and higher-order corrections to the Higgs production cross sections (the so-called K-factors), which are expected to increase for example the $gg \rightarrow H \rightarrow \gamma\gamma$ rate by a factor of about two compared to leading order, have not been included. Nevertheless, it will not be easy to extract a convincing signal with only 10 fb^{-1} , because the significances of the individual channels are small, and because an excellent knowledge of the backgrounds and close-to-optimal detector performances are required, as discussed below. Therefore, the contribution of both experiments, and the observation of possibly all three channels, will

Table 4: For a Higgs boson mass of 115 GeV and an integrated luminosity of 10 fb^{-1} , the expected numbers of signal (S) and background (B) events after all cuts and signal significances (S/\sqrt{B}) in ATLAS for the three dominant channels.

	$H \rightarrow \gamma\gamma$	$t\bar{t}H \rightarrow t\bar{t}b\bar{b}$	$qqH \rightarrow qq\tau\tau \rightarrow \ell + X$
S	130	15	~ 10
B	4300	45	~ 10
S/\sqrt{B}	2.0	2.2	~ 2.7

be crucial for an early discovery.

The channels listed in tab. 4 are complementary. They are characterized by different Higgs production mechanisms and decay modes, and therefore by different backgrounds and different detector requirements. Good uniformity of the electromagnetic calorimeters is crucial for the $H \rightarrow \gamma\gamma$ channel, as already mentioned. Powerful b -tagging is the key performance issue for the $t\bar{t}H$ channel, since there are four b -jets in the final state which all need to be tagged in order to reduce the background. Efficient and precise jet reconstruction over ten rapidity units ($|\eta| < 5$) is needed for the $H \rightarrow \tau\tau$ channel, since tagging the two forward jets accompanying the Higgs boson and vetoing additional jet activity in the central region of the detector are necessary tools to defeat the background. Finally, all three channels demand relatively low trigger thresholds (at the level of 20-30 GeV on the lepton or photon p_T), and a control of the backgrounds to a few percent. These requirements are especially challenging during the first year(s) of operation.

9. Conclusions

The LHC offers the potential for very interesting physics and major discoveries right from the beginning. We note that for some standard physics processes, a single day of data taking at $L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ corresponds, in terms of event statistics, to ten years of operation at previous machines. SUSY may be discovered quickly, a light Higgs boson will be much more difficult to observe, unexpected scenarios and surprises may also be round the corner at an unprecedented collider exploring a completely new territory.

The machine luminosity performance will be the crucial issue at the beginning. Hopefully, an instantaneous luminosity of up to $L \sim 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, and an integrated luminosity of a few fb^{-1} per experiment, can be achieved by the end of 2008, as estimated by the accelerator team.

Concerning the experiments, a lot of emphasis has been given to quality checks in the various phases of the construction and to tests with beams. The results indicate that the detectors “as built” should give a good starting-point performance already on “day 1”. However, a lot of data and time will be needed to commission the detectors, the triggers and the software *in situ*, to reach the performance required to address serious physics studies, to understand standard physics and the Monte Carlo tools at $\sqrt{s}=14 \text{ TeV}$, and to measure the backgrounds to possible new physics processes.

The next challenge is therefore an efficient and timely detector commissioning, from cosmics runs to first collisions, where the experiments try to learn and fix as much as possible as early as possible. In parallel, efforts to improve and tune the Monte Carlo generators, based on theoretical developments as well as on comparisons with data from past and present experiments, should be pursued with vigor. Indeed, both activities will be crucial to reach quickly the discovery phase, and to extract convincing signals of new physics in the first year(s) of operation.

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